ESTIMATION OF POWER GENERATION POTENTIAL OF NON-WOODY BIOMASS AND COAL-BIOMASS MIXED BRIQUETTES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

MASTER OF TECHNOLOGY

in

Mechanical Engineering

by

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DEPARTMENT OF MECHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA, ORISSA-769008

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CERTIFICATE

This is to certify that the thesis entitled **"Estimation of Power Generation Potential of Non- Woody Biomass and Coal – Biomass Mixed Briquettes"** submitted by **Mr. Bablu Das** in partial fulfilment of the requirements for the award of **Master of Technology Degree** in **Mechanical Engineering** with specialization in **"Thermal Engineering"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under our supervision and guidance.

To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

In view of energy and environmental problems associated with the use of fossil fuels (coal, petroleum and gas) in power generation, an increasing attention is being paid world-over by the scientists and technocrats for the utilisation of renewable energy sources in power generation, metallurgical industries etc. There are various type of renewable energy sources such as solar, wind, hydropower, biomass energy etc. out of these renewable energy sources, biomass is more economically viable for almost all the continents in the world. Biomass is a carbonaceous material and provides both the thermal energy and reduction for oxides, where as other renewable energy sources can meet our thermal need only. Amongst all the solid fuel like coal etc. biomass is the purest fuel consisting of very lesser amount of ash materials. The power generation potential data for renewable energy sources in India clearly indicates that the biomass has potential to generate more than 17000 MW of electricity per year in India. However, the country is locking in exploitation of biomass in power generation. Till date, India has been capable to generate only 2000 MW (approx.) of electricity per year in spite of declaration of several incentives by the govt. of India. Hence, there is an argent need to increase the utilization of biomass in power generation. The present project work is a positive step towards energy and environmental problems facing the world. The presently selected forestry biomass species has no any commercial use and are underutilized.

Presently, co-firing (coal + biomass) has been proved to be more attractive and economically viable technique for power generation. In the present work, briquettes were prepared by mixing non-coking coal from Orissa mines and the related biomass species in different ratio (coal: biomass = 95:05, 90:10, 85:15, 80:20). The objectives have been to examine their energy values and power generation potential.

3rd chapter of this theses deal with the experimental work carried out in completion of this project work. The experimental works included determination of proximate analysis, energy value & ash fusion temperature (AFT) of different components of biomass, coal & there mixture.

The results & discussion of the experimental work have been outlined in chapter 3 of the thesis. The results has indicated that Cassia Tora biomass species has somewhat higher ash and lower fixed carbon contents then these of Gulmohar biomass species, energy values of Gulmohar biomass species were found to be little bit higher than that of Cassia Tora biomass. The proximate analysis results of studied coal proved it of F- grade.

As it is evident from result, an increase in biomass content (wood/leaf/nascent branch), in general, in the briquetted increases the energy values of the resulting briquettes. From Volatile Matter (VM) & Fixed Carbon result, it appears that the volatile matter contents is also playing significant role in affecting the energy value of the briquettes in addition to fixed carbon. Among the four AFTs (IDT, ST, HT & FT), softening temperature of ash is most important for boiler operation. The results have indicated that both biomass species have more or less same softening temperature but lower than that of coal. Increase in biomass content in the briquette on rang studied has slightly reduced the softening temperature. The softening temperature results of the briquettes also indicated that the boiler could be safely operated up to about 1100 ^{0}C with studied (Coal + Biomass) briquette.

The conclusion derived from present project work has been presented in Chapter 4 of this thesis.

Keywords: proximate analysis, ash fusion temperature, electricity generation, energy content, non-woody biomass species.

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CHAPTER-1

INTRODUCTION

1.1 INTRODUCTION

India being a developing nation, sustainable development is more important. Energy is a basic requirement for economic development. Every sector of Indian economy – agriculture, industry, transport, commercial and domestic – needs inputs of energy. Energy is an important factor for any developing country. Ever increasing consumption of fossil fuels and rapid depletion of known reserves are matters of serious concern in the country. This growing consumption of energy has also resulted in the country becoming increasingly dependent on fossil fuels such as coal and oil and gas. Rising prices of oil and gas and potential shortages in future lead to concerns about the security of energy supply needed to sustain our economic growth. Increased use of fossil fuels also causes environmental problems both locally and globally. Biomass has always been an important energy source for the country considering the benefits it offers. Biomass provides both, thermal energy as well as reduction for oxides. It is renewable, widely available, carbon-neutral and has the potential to provide significant employment in the rural areas. Biomass is also capable of providing firm energy. About 32% of the total primary energy use in the country is still derived from biomass. Ministry of New and Renewable Energy has realised the potential and role of biomass energy in the Indian context and hence has initiated a number of programmes for promotion of efficient technologies for its use in various sectors of the economy to ensure derivation of maximum benefits Biomass power generation in India is an industry that attracts investments of over Rs.600 crores every year, generating more than 5000 million units of electricity and yearly employment of more than 10 million man-days in the rural areas. For efficient utilization of biomass, bagasse based cogeneration in sugar mills and biomass power generation have been taken up under biomass power and cogeneration programme.

1.2 DIFFERENT RENEWABLE ENERGY SOURCES

Renewable energy sources are continuously replenished by natural processes. For example, solar energy, wind energy, bio-energy – bio fuels, hydropower etc., are some of the examples of renewable energy sources. In view of energy and environmental problems associated with the use of fossil fuels in power generation, scientist and technocrats, world over, are in search of the suitable substitute of fossil fuels for power generation. The various forms of renewable energy sources having a potential to be utilized in power generation are as follows:

- Wind Energy
- Solar Energy
- Hydropower
- Geothermal Energy
- Nuclear Energy
- Biomass and Bio-energy

1.2.1 Biomass and Bio-energy

Biomass is renewable organic matter derived from trees, plants, crops or from human, animal, municipal and industrial wastes. Biomass can be classified into two types, woody and non-woody. Woody biomass is derived from forests, plantations and forestry residues. Non-woody biomass comprises agricultural and agro industrial residues and animal, municipal and industrial wastes.

Biomass does not add carbon dioxide to the atmosphere as it absorbs the same amount of carbon in growing as it releases when consumed as a fuel. Its advantage is that it can be used to generate electricity with the same equipment that is now being used for burning fossil fuels. Biomass is an important source of energy and the most important fuel worldwide after coal, oil and natural gas. Bio-energy, in the form of biogas, which is derived from biomass, is expected to become one of the key energy resources for global sustainable development. Biomass offers higher energy efficiency through form of Biogas than by direct burning.

Biomass contains stored energy from the sun. Plants absorb the sun's energy in a process called photosynthesis. The chemical energy in plants gets passed on to animals and people who eat these plants. Biomass is a renewable energy source because we can always grow more trees and crops and waste will always exist. Some examples of biomass fuels are wood, crops, manure and some garbage. When burned, the chemical energy in biomass is released as heat. In a fireplace, the wood that is burnt is a biomass fuel. Wood waste or garbage can be burnt to produce steam for making electricity, or to provide heat to industries and homes. Burning biomass is not the only way to release its energy. Biomass can be converted to other usable forms of energy like methane gas or transportation fuels like ethanol and biodiesel. Methane gas is the main ingredient of natural gas. Smelly stuff, like rotting garbage and agricultural and human waste, release methane gas - also called "landfill gas" or "biogas." Crops like corn and sugar cane can be fermented to produce the transportation fuel, ethanol. Biodiesel, another transportation fuel, can be produced from left-over food products like vegetable oils and animal fats. Biomass fuels provide about 3 percent of the energy used in the United States. People in USA are trying to develop ways to burn more biomass and less fossil fuel. Using biomass for energy can cut back on waste and support agricultural products grown in the United States. Biomass fuels also have a number of environmental benefits.

1.3 POWER GENERATION POTENTIAL FROM BIOMASS AND BAGASSE BASED COGENERATION

Biomass resources are potentially the world's largest and most sustainable energy sources for power generation in the 21st century (*Hall & Rao, 1999*). The current availability of biomass in India is estimated at about 500 million metric tonnes per year. Studies sponsored by the Ministry has estimated surplus biomass availability at about 120 – 150 million metric tonnes per annum covering agricultural and forestry residues corresponding to a potential of about 17,000 MW. This apart, about 5000 MW additional power could be generated through bagasse based cogeneration in the country's 550 Sugar mills, if these sugar mills were to adopt technically and economically optimal levels of cogeneration for extracting power from the bagasse produced by them (Ministry of New and Renewable Energy). The details of the estimated renewable energy potential and cumulative power generation in the country have been outlined in Table1.1 (*MNRE, 2011*), indicating that the available biomass has a potential to generate around 17,000 MW of electricity.

The Ministry has been implementing biomass power/co-generation programme since mid-nineties. A total of 288 biomass power and cogeneration projects aggregating to 2665 MW capacity have been installed in the country for feeding power to the grid consisting of 130 biomass power projects aggregating to 999.0 MW and 158 bagasse cogeneration projects in sugar mills with surplus capacity aggregating to 1666.0 MW. In addition, around 30 biomass power projects aggregating to about 350 MW are under various stages of implementation. Around 70 Cogeneration projects are under implementation with surplus capacity aggregating to 800 MW. States which have taken leadership position in implementation of bagasse cogeneration projects are Andhra Pradesh, Tamil Nadu, Karnataka, Maharashtra and Uttar Pradesh. The leading States for biomass power projects are Andhra Pradesh, Chhattisgarh, Maharashtra, Madhya Pradesh, Gujarat and Tamil Nadu (http://mnre.gov.in/prog-biomasspower.htm).

Table 1.1: Electricity Generation Potentials of Renewable Energy Sources in India

Renewable Energy Programme/ Systems	**Target for 2010-11**	**Achievement during March 2011**	**Total achievement during 2010-11**	**Cumulative achievement up to 31.03.2011**	**Potential (MW)**
A. GRID-INTERACTIVE POWER (CAPACITIES IN MW)					
Wind Power	2000	872.68	2350.35	14157.10	45195
Small Hydro Power	300	56.70	307.22	3042.63	15000
Biomass Power	**455**	**-**	**143.50**	**997.10**	**16881**
Bagasse Cogeneration		31.50	321.50	1667.53	5000
Waste to Power - Urban	17	-	-	19.00	2700
-Industrial		-	7.50	53.46	
Solar Power (SPV)	200*	5.29	26.59	37.66	
Total	**2972**	**966.17**	**3156.66**	**19974.48**	

Source: MNRE, Figures at the end of March, 2011

Renewable Energy Programme/ Systems	**Target for 2010-11**	**Achievement during March 2011**	**Total achievement during 2010-11**	**Cumulative achievement up to 31.03.2011**
B. OFF-GRID/ CAPTIVE POWER (CAPACITIES IN $MW_{EQ)}$				
Waste to Energy -Urban	13.00	-	-	3.50
-Industrial		0.83	23.70	66.92
Biomass(non-bagasse)Cogeneration	75.00	11.69	80.73	301.61
Biomass Gasifiers -Rural	4.00	0.40	1.37	14.47
- Industrial	15.00	3.25	9.00	117.34
Aero Genrators/Hybrid systems	0.50	0.05	0.05	1.12
SPV Systems (>1kW)	32.00	1.25	2.60	5.80
Water mills/micro hydel	2.50	0.17(34nos)	2.2(444nos)	6.98(1397)
Total	**142.00**			

Source: MNRE, Figures at the end of March, 2011

Table 1.2: State-wise/Year-wise List of Commissioned Biomass Power/Cogeneration Projects in MW

(as on 31.03.2011)

S.No.	State	Upto 31.03.2003	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	Total
1	Andhra Pradesh	160.05	37.70	69.50	12.00	22.00	33.00	9.00	20.00	..	363.25
2	Bihar		--	--	--	--	--	--	--	9.50	9.50
3	Chattisgarh	11.00	--	--	16.50	85.80	33.00	9.80	43.80	32.00	231.90
4	Gujarat	0.50	--	--	--	--	--	--	--	--	0.50
5	Haryana	4.00	--	2.00	--	--	--	--	1.8	28.00	35.80
6	Karnataka	109.38	26.00	16.60	72.50	29.80	8.00	31.90	42.00	29.00	365.18
7	Madhya Pradesh		1.00	--	--	--	--	--	--	--	1.00
8	Maharashtra	24.50	--	11.50	--	40.00	38.00	71.50	33	184.50	403.00
9	Punjab	22.00	--	--	6.00	--	--	--	34.50	12.00	74.50
10	Rajasthan		7.80	--	7.50	8.00	--	8.00	--	42.00	73.30
11	Tamil Nadu	106.00	44.50	22.50	--	42.50	75.00	43.20	62.00	92.50	488.20
12	Uttarakhand	--	--	--	--	--	--	--	--	10.00	10.00
13	Uttar Pradesh	46.50	12.50	14.00	48.50	--	79.00	172.00	194.50	25.50	592.50
14	West Bengal		--	--	--	--	--	--	16.00	--	16.00
	Total	**483.93**	**129.50**	**136.10**	**163.00**	**228.10**	**266.00**	**345.40**	**447.60**	**465.00**	**2664.63**

Source: MNRE, Figures at the end of March, 2011

1.4 BIOMASS: CLASSIFICATION AND PROPERTIES

The overall biomass resources can be broadly categorized into two parts based on its availability in the natural form.

1.4.1 Woody biomass and Non-woody biomass

- **Woody biomass**

Woody biomass is characterized by high bulk density, less void age, low ash content, low moisture content, high calorific value. Because of the multitude of advantages of woody biomass its cost is higher, but supply is limited. Woody biomass is a preferred fuel in any biomass-to energy conversion device; however its usage is disturbed by its availability and cost.

- **Non-woody biomass**

The various agricultural crop residues resulting after harvest, organic fraction of municipal solid wastes, manure from confined livestock and poultry operations constitute non-woody biomass. Non-woody biomass is characterized by lower bulk density, higher void age, higher ash content, higher moisture content and lower calorific value. Because of the various associated drawbacks, their costs are lesser and sometimes even negative.

1.4.2 Biomass properties

An understanding of the structure and properties of biomass materials is necessary in order to evaluate their utility as chemical feed stocks. Chemical analysis, heats of combustion and formation, physical structure, heat capacities and transport properties of biomass feed stocks and chars are more relevant in the gasification of any biomass.

- **Bulk chemical analysis**

In evaluating gasification feed stocks, it is generally useful to have proximate and ultimate analyses, heats of combustion and sometimes ash analyses. These provide information on volatility of the feedstock, elemental composition and heat content. The elemental analysis is particularly important in evaluating the feedstock in terms of potential pollution. The low energy density of biomass makes them less preferred by the people when compared to fossil fuels like gas, oil and coal.

- **Physical properties**

The major physical data necessary for predicting the thermal response of biomass materials under pyrolysis, gasification and combustion reactions are shape, size, void age, thermal conductivity, heat capacity, diffusion coefficient and densities viz. bulk density, apparent particle density and true density. The values of these properties are different for different biomass especially in the case of loose biomass.

- **Biochemical analysis**

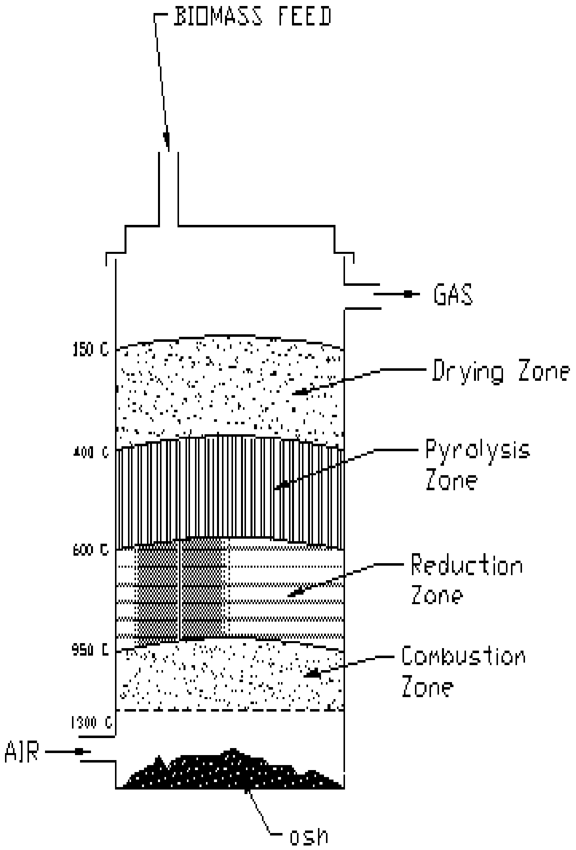
As biomass is a natural material, many highly efficient biochemical processes have developed in nature to break down the molecules of which biomass is composed and many of these biochemical conversion processes can be harnessed. Biochemical conversion makes use of the enzymes of bacteria and other micro-organisms to break down biomass. In most cases micro-organisms are used to perform the conversion process: anaerobic digestion, fermentation and composting.

1.5 BIO-ENERGY TECHNOLOGIES FOR DECENTRALIZED POWER GENERATION

The advances in bio-energy technologies (BETs) over the last few decades have enabled a significant increase in the utilization of biomass for power generation. Key technologies available for promoting power generation from biomass in India are gasification, combustion, co-firing and bio-methanation.

1.5.1 Gasification

Biomass gasifiers are devices promoting thermo-chemical conversion of biomass into high energy combustible gas for burning in gas turbine (BIG / GT). Biomass, particularly woody biomass, can be converted to high-energy combustible gas for use in internal combustion engines for mechanical or electrical applications. Biomass gasifiers are devices performing thermo-chemical conversion of biomass through the process of oxidation and reduction under sub-stoichiometric conditions. Gasifiers are broadly classified into updraft, downdraft and cross draft (shown in Figs. 1.1 - 1.3) types depending on the direction of airflow. Gasifier systems with various capacities in the range of 1 kg/h to about 500 kg/h are presently in use. These systems are used to meet both power generation using reciprocating engines or for direct usage in heat application. The prime movers are diesel engines connected to alternators, where diesel savings up to 80% are possible. Among the biomass power options, small-scale gasifiers (of 20–500 kW) have the potential to meet all the rural electricity needs and leave a surplus to feed into the national grid. The total installed capacity of biomass gasifier systems as of 2011 is nearly 130 MW.



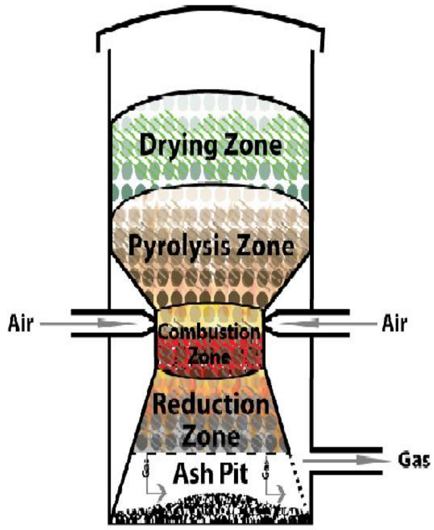


Fig.1.1: Updraft Gasifier

Fig.1.2: Downdraft Gasifier

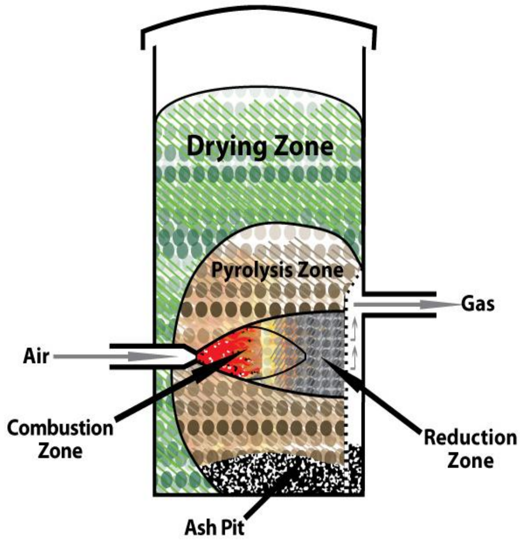


Fig.1.3: Crossdraft Gasifier

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are:

a) Drying of fuel
b) Pyrolysis – a process in which tar and other volatiles are driven off
c) Combustion
d) Reduction

- **Drying of fuel**

The first stage of gasification is drying. Usually air-dried biomass contains moisture in the range of 7-15 %. The moisture content of biomass in the upper most layers is removed by evaporation using the radiation heat from oxidation zone. The temperature in this zone remains less than 120 °C.

- **Pyrolysis**

The process by which biomass loses all its volatiles in the presence of air and gets converted to char is called pyrolysis. At temperature above 200°C, biomass starts losing its volatiles. Liberation of volatiles continues as the biomass travels almost until it reaches the oxidation zone. Once the temperature of the biomass reaches 400°C, a self-sustained exothermic reaction takes place in which the natural structure of the wood breaks down. The products of pyrolysis process are char, water vapour, Methanol, Acetic acid and considerable quantity of heavy hydrocarbon tars.

- **Combustion**

The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen, usually as steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1400 °C. The main reactions, therefore, are:

$$C + O_2 = CO_2 \text{ (+ 393 MJ/kg mole)} \qquad (1)$$

$$2H_2 + O_2 = 2H_2O \text{ (- 242 MJ/kg mole)} \qquad (2)$$

- **Reduction:**

The products of partial combustion (water, carbon dioxide and un-combusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place:

$$C + CO_2 = 2CO \ (- 164.9 \text{ MJ/kg mole}) \quad (3)$$

$$C + H_2O = CO + H_2 \ (- 122.6 \text{ MJ/kg mole}) \quad (4)$$

$$CO + H_2O = CO + H_2 \ (+ 42 \text{ MJ/kg mole}) \quad (5)$$

$$C + 2H_2 = CH_4 \ (+ 75 \text{ MJ/kg mole}) \quad (6)$$

$$CO_2 + H_2 = CO + H_2O \ (- 42.3 \text{ MJ/kg mole}) \quad (7)$$

Reactions (3) and (4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the reduction zone are normally 800-10000C. Lower the reduction zone temperature (~ 700-8000C), lower is the calorific value of gas.

1.5.2 Combustion: Steam Turbine System

The combustion technology is similar to coal-based thermal power production technology, in which the biomass is burnt in the boiler and produce steam, which is used to drive a turbine to produce electricity. The extend of biomass-based combustion systems is low with only about 466MW installed until 2007. The typical size of these plants is ten times smaller (from 1 to100 MW) than coal-fired plants because of the limited accessibility of local feedstock and the high transportation cost. A few large-scale such thermal or CHP plants are in operation. The small size roughly doubles the investment cost per kW and results in lower electrical effectiveness compared to coal plants. Plant efficiency is around 30% depending on plant size. This technology is used to dispose of large amounts of residues and wastes (e.g. bagasse). Using high-quality wood chips in modern combined heat and power (CHP) plants with highest steam temperature of 540°C, electrical efficiency can reach 33%-34% (LHV) and up to 40% if operated in electricity-only mode. Fossil energy consumed for bio-energy production using agriculture and forestry products can be as low as 2%-5% of the final energy produced. Based on life-cycle assessment, net carbon emissions per unit of electricity are below 10% of the emissions from fossil fuel-based electricity. When using MSW, corrosion problems limit the steam temperature and decrease electrical efficiency to around 25%. New CHP plant designs using MSW are expected to reach 25%-30% electrical efficiency and above 85%-90% overall efficiency in CHP mode if good similar is achieved between heat generation and demand. Electricity generation from MSW offers a net emission saving between 725 and 1520 kg CO2/t MSW. reduction is even higher for CHP.

1.5.3 Co-Firing

Biomass conversion into biogas can be either from fast thermo-chemical processes (e.g., pyrolysis1) which can produce biogas and other fuels, with only 2%-4% of ash, or from slow anaerobic fermentation - which converts only a fraction (50%-60%) of feedstock but produces soil conditioners as a by-product. The biogas can be used in combustion engines (10 kW to 10 MW) with efficiency of some 30%-35%; in gas turbines at higher efficiencies or in highly-efficient combined cycles. Biomass integrated gasification gas turbines (BIG/GT) are not yet in commercial use, but their economics is expected to improve. The first integrated gasification combined cycle (IGCC) running on 100% biomass (straw) has been successfully operated in Sweden. IGCC plants are already economically competitive in CHP mode using black-liquor from the pulp and paper industry as a feedstock. Other developments have brought Stirling engines and organic Rankine cycles (ORC) closer to the market whereas integrated gasification fuel cell plants (IGFC) still need significantly more R&D.

Advantages of co-firing the combustion of two different types of materials at the same time. One of the advantages of co-firing is that an existing plant can be used to burn a new fuel, which may be cheaper or more environmentally friendly. For example, biomass is sometimes co-fired in existing coal plants instead of new biomass plants. Co-firing can also be used to improve the combustion of fuels with low energy content. For example, landfill gas contains a large amount of carbon dioxide, which is non-combustible. If the landfill gas is burned without removing the carbon dioxide, the equipment may not perform properly or emissions of pollutants may increase. Co-firing it with natural gas increases the heat content of the fuel and improves combustion and equipment performance. As long as the electricity or heat produced with the biomass and landfill gas was otherwise going to be produced with non-renewable fuels, the benefits are essentially equivalent whether they are co-fired or combusted alone. Also, co-firing can be used to lower the emission of some pollutants. For example, co-firing biomass with coal results in less sulphur emissions than burning coal by itself.

Two distinct techniques are available to co-fire bio-fuels in utility boilers:

(i) direct co-firing, biomass fuels are blended with coal in coal yard and the blend is sent to the firing system Fig.1.4 and

(ii) Indirect co-firing, the biomass is prepared separately from the coal and injected into the boiler without impacting the coal delivery process Fig. 1.5. The first approach, in general, is used with less than 5 wt. % co-firing.

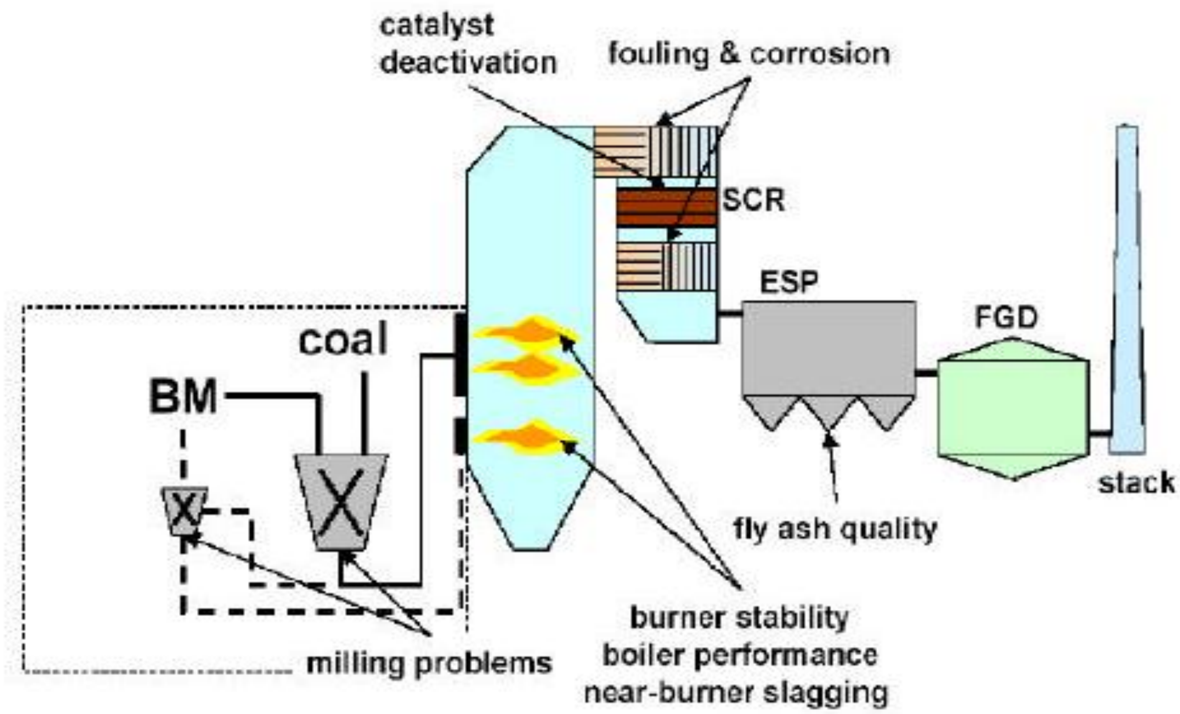


Fig. 1.4: Direct Co-firing System

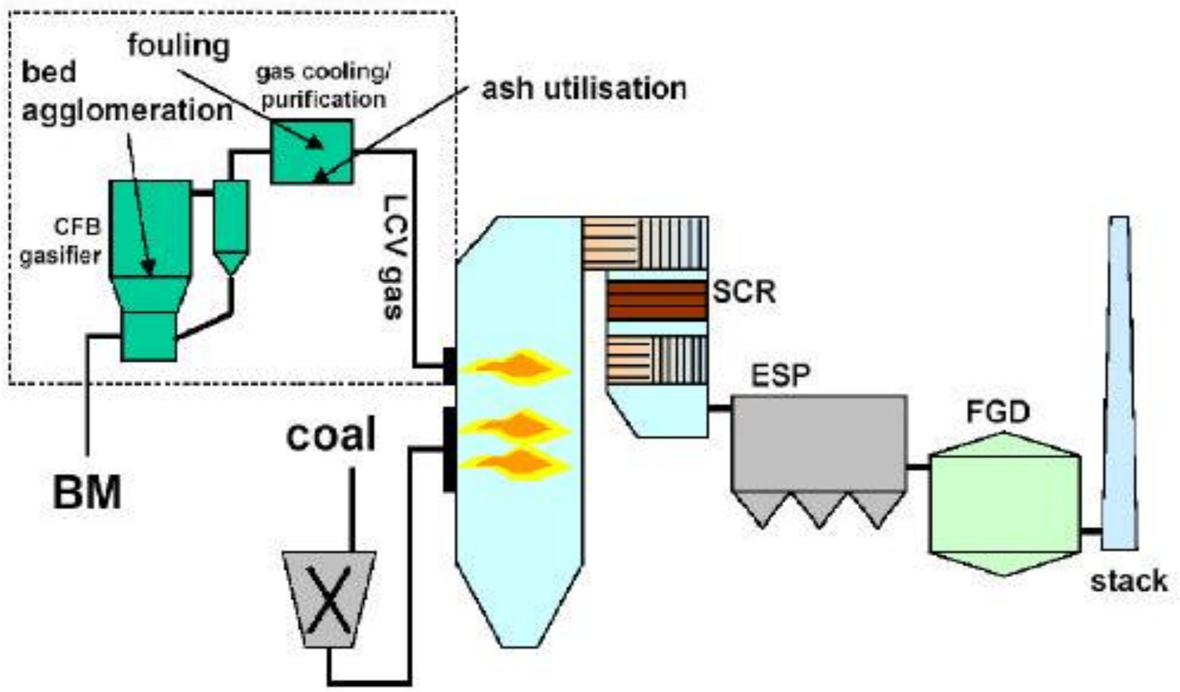


Fig.1.5: Indirect Co-firing System

1.5.4 Bio-methanation

It is the technology of biogas (a mixture of 60% methane and 40% carbon dioxide gas) production through anaerobic fermentation of cellulosic materials, such as animal dung, plant and vegetable wastes, etc. (*Ravindranath and Balachandra, 2009*) and combustion of this gas for electricity generation. The anaerobic digestion of waste has the disadvantages of large installation cost, longer reaction time, high amount of water requirement and large area for installing the plant. Except for a few demonstration projects, hardly any potential has been exploited till now in India.

1.6 FEEDSTOCK & PROCESSES

Biomass resources include woody, non- woody and animal manure, residues from food and paper industries, agricultural residues, wood wastes from industry and forestry, municipal wastes, sewage sludge, sugar crops (sugar cane, beet, sorghum), dedicated energy crops such as short-rotation (3-15 years) coppice (willow, eucalyptus, poplar), grasses (Miscanthus), oil crops (soy, sunflower, oilseed rape, jatropha, palm oil) and starch crops (corn, wheat). Residues and organic wastes have been the key biomass sources so far, but energy crops are achievement importance and market share. With re-planting, biomass combustion is a carbon-neutral process as the CO_2 emitted has until that time been absorbed by the plants from the atmosphere. Residues, wastes, bagasse are primarily used for heat & power generation. Starch sugar, and oil crops are primarily used for fuel production. Cheap, high-quality biomass (e.g., wood waste) for power production may become limited as it is also used for heat production and in the paper industry and pulp industry. New resources based on energy crops have larger potential but are more costly. Technologies and cost of heat and power generation from biomass depend on availability feedstock quality, and transportation cost, power plant size, conversion into biogas (if any). If adequate biomass is available, bio power and CHP plants are a clean and reliable power source suitable for base-load service.

Fig.1.6 shows that different feedstock and different types of process for heat and power generation from biomass.

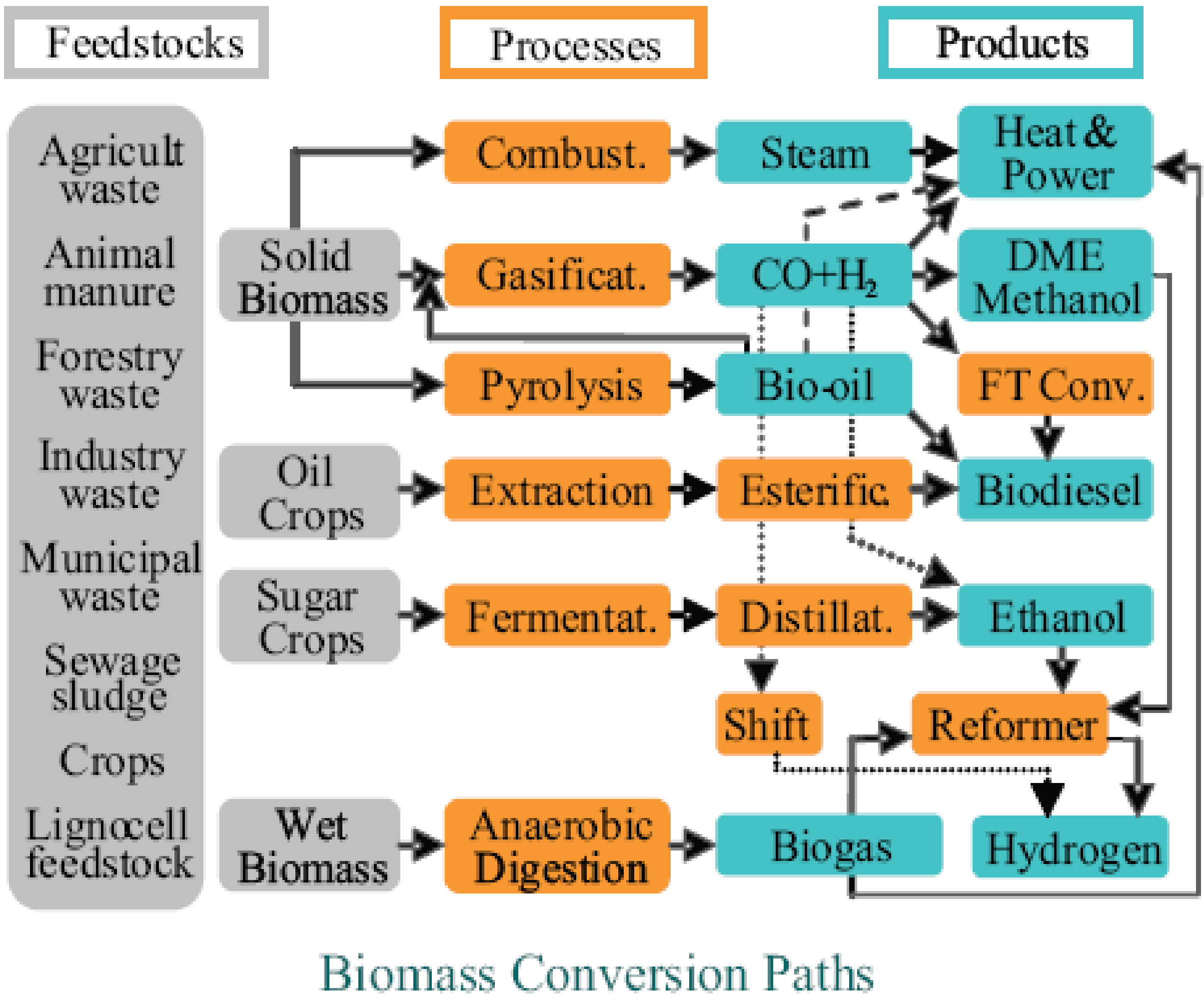


Fig.1.6: Feedstock & Processes

1.7 BIOMASS-A SOURCE OF POWER GENERATION IN SMALL SCALE INDUSTRIES

In India, there are over 11 million small-scale registered industrial units that provide employment to more than 27 million people (Kumar & Patel, 2008). They contribute to 40% of the country's industrial production and 34% of exports. A major number of these units require large quantities of electrical energy. The high cost of supply, which is mostly unpredictable and unreliable on account of scheduled / unscheduled power cuts, drives industries to invest in imprisoned power generation. As fossil fuels are limited and polluting, such order provides an attractive platform to renewable for providing different energy solutions to particularly small and medium enterprises, industrial and commercial establishments. Biomass energy systems can be deployed to meet power requirement in industries. Such electricity generation will help industries in becoming independent and relieve pressure on fossil fuels.

The captive biomass-based energy units having capacity ranging from about 100 KW to few MW can be set-up by an industrial unit. In general, combustion-based systems are suited for MW-scale projects, whereas gasifiers are appropriate for small and decentralized power projects up to 1 MW capacity. In addition to electricity, the bio-power plant is also likely to produce activated carbon (a valuable product) that further offsets the working cost of the plant.

Under a broad rural development policy, the increase in crop diversity agricultural productivity, crop diversity and the generation of rural income and employment have been given high priority in many developing countries. Promoting and improving rural industries, naturally, is an important strategy for attaining such policy objectives. The majority of small industries are in peri-urban and rural areas. For fuel, majority still uses wood and agricultural residues. The traditional processes in small-scale industries are often traditional and operate under highly competitive conditions. They must compete with both similar scale producers as well as larger scale producers using more modern and technically advanced production facilities. They are relatively isolated from the source of skills, know-how and technology that would allow improvements in their operations, energy, etc. In addition, the very nature and location of the small industries often reinforce their isolation from formal sources of financial, technical and other assistance. Yet, small industries have been recognized to have important role in the growth and stability of national, rural economies and the survival of subsistent economies. The sector provides income and/or local employment to many people. It has also been found that biomass energy typically generates 10 times more employment than oil and coal *(de Castro et. Al., 1999)*.For developing countries, the use of biomass energy sources could also reduce dependency on imported energy sources *(de Castro et al., 1999).*On the other hand, it is also true that shortage of fuels, in the forms of fuel wood and other biomass are threatening the sustainability of small industries. For example, there have been cases in Cambodia of small enterprises closing down due to fuel shortage (WeNetCam, 2000). It was also reported that some areas in Nepal where small industries were concentrated, suffered from environmental degradation due to fuel wood extraction for industrial operations (Donovan in BEST, 1989).Thus, technology that could assist them in heightening their efficiency and output, accurate study and documentation of industrial stoves is a necessary step at this time.

Gasification-based small modular biomass systems are emerging as a promising technology to supply electricity and heat to rural areas, businesses and the billions of people who live without power worldwide. Biomass Program support through subcontracted efforts with private sector companies over the past several years, has advanced several versions of the technology to the point where they are now approaching commercialization. By adopting a standardized modular design, these 5 kW-to-5 MW systems are expected to lend themselves to high volume manufacturing techniques to bring them on a competitive level with large standalone plants. Using locally available biomass fuels such as wood, crop waste, animal manures and landfill gas, small modular systems can be brought to the source of the fuel rather than incurring transportation costs to bring biomass fuels to a large centrally located plant. Small modular biomass systems also fulfil the great market potential for distributed, on-site, electric power and heat generation throughout the world. Small modular biomass systems typically convert a solid biomass fuel into a gaseous fuel through a process called gasification. The resulting gas, comprised primarily of carbon monoxide and hydrogen, is then cleaned before use in gas turbine or internal combustion engine connected to an electrical generator. Waste heat from the turbine or engine can also be captured and directed to useful applications. Small modular systems lend themselves to such combined heat and power operations much better than large central facilities.

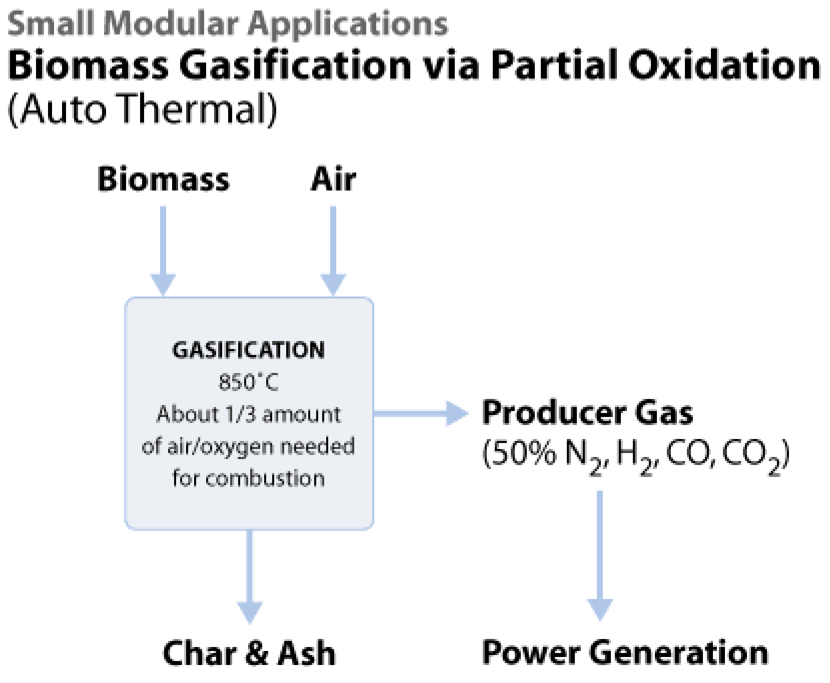


Fig. 1.7: Small Modular Applications

Small Modular biomass systems offer many benefits to potential customers. They have minimal environmental impact when compared to other existing technologies using coal or biomass as the fuel. On the one hand, economics can be attractive when owners connect the unit to a power grid that will buy unused power. On the other, small modular systems can electrify isolated areas for which the cost of connection to the grid is prohibitive. Another economic benefit may be realized if the customer has a biomass waste stream that can be converted into a source of energy rather than being an economic burden. The flexibility to use more than one fuel also appeals to many users. Modern microprocessor control has been coupled to gasification technology to result in systems requiring minimal operator attention. And, in off-grid locations small modular biomass systems offer the potential for lights, refrigeration, heat and power to enable small cottage industries to become economically viable.

1.8 BIOMASS- ENVIRONMENTAL AND CLIMATE CHANGE BENEFITS

Over the past few years, people throughout the world have become very much aware of the terms 'global warming' and 'greenhouse gases'. This has to do with what is going into the atmosphere and how it affects our way of life. When fossil fuels are burned they send carbon dioxide (CO_2), sulphur oxides (SOx), NOx emissions and ash production into the atmosphere. It is believed that these emissions stay there for tens of thousands of years and are creating a barrier, which separates the earth from the sun. Reducing this threat to the atmosphere is one of the Environmental Benefits of Biomass.

Air/Atmospheric Pollution is a major challenge faced by the world today and impacts all of us in so many different ways. Importantly, our ability to effectively address air pollution is fundamental to our pursuit of promoting sustained economic growth and sustainable development. Our approach in dealing with pollution issues is, therefore, built around the high priority accorded by developing countries to economic growth and poverty eradication. The decisions concerning the fight against air/atmosphere pollution should be guided by the understanding that economic development, social development and environmental protection are interdependent and mutually reinforcing components of sustainable development. Air pollution has serious negative impacts on human health, socio-economic development, ecosystems and cultural heritage. Urgent and effective actions are, therefore, required in regard to both indoor air pollution from traditional biomass cooking and heating and ambient air pollution from all sources. Indoor air pollution, we believe, must be accorded high priority, as it is in its worst form, a poverty-related manifestation. Air pollution is also increased by factors such as: natural disasters including volcanic eruptions, sand storms, desertification and land degradation, which cause health problems and disrupt peoples' daily lives.

Environmentally, biomass has some advantages over fossil fuels such as coal and petroleum. Biomass contains little sulphur and nitrogen, so it does not produce the pollutants that cause acid rain. Growing plants for use as biomass fuels may also help keep global warming in check. That's because plants remove carbon dioxide--one of the greenhouse gases-from the atmosphere when they grow. The combustion (direct or indirect) of biomass as a fuel also returns CO_2 to the atmosphere. However this carbon is part of the current carbon cycle: it was absorbed during the growth of the plant over the previous few months or years and, provided the land continues to support growing plant material, a sustainable balance is maintained between carbon emitted and absorbed. Biomass is practically free from sulphur, nitrogen and heavy metals (Hg, etc.) and has much lower ash content (1-3 wt. %) than coal (Kumar and Gupta, 1993). Hence, unlike fossil fuels, biomass use in electricity generation is not likely to pollute the atmosphere with SOx, NOx, SPM, etc.

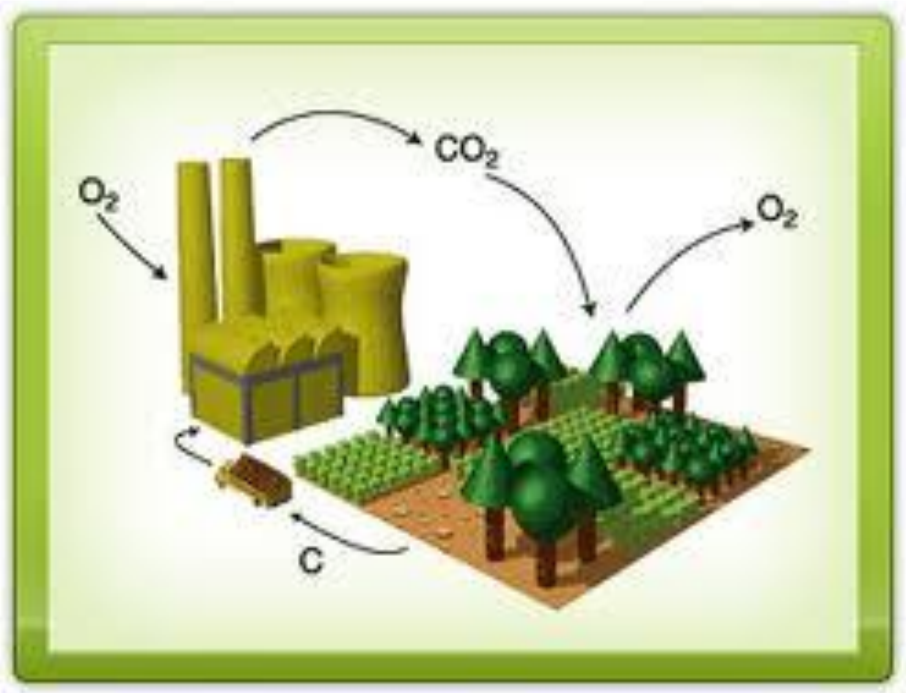


Fig. 1.8: Carbon Cycle Diagram

As trees in the energy plantation grow, they absorb carbon dioxide from the atmosphere. During photosynthesis the trees store carbon in their woody tissue and oxygen is released back to the atmosphere. At harvest, wood fuel is transported from the plantation to the heat or power generating plant. As the wood is burned at the heat or power generating plant the carbon stored in the woody tissue combines with oxygen to produce carbon dioxide, this is emitted back to the atmosphere in the exhaust gases. The amount of additional biomass that grows over the course of a year in a given area is known as the annual increment. Provided the amount consumed is less than the annual increment its use can be sustainable and biomass can be considered a low carbon fuel and biomass $CO2$ absorption and emission is in balance.

1.9 ADVANTAGES OF DECENTRALIZED BIOMASS POWER GENERATION SYSTEMS

The biomass-based decentralized power generation systems are expected to provide the following multiple social, economic and environmental benefits to the village people:

- Electricity for lighting and development of small-scale industries, thus making the villagers / small industries self-dependent.
- Growth of biomass occurs through photosynthesis reaction. Here, the biomass absorbs Carbon dioxide from the atmosphere and gives out oxygen. Thus the sustainable generation and use of biomass in power plants will definitely help in reducing carbon dioxide concentration in the atmosphere and thus the greenhouse effect.
- In comparison to coal, the ash content in biomass is very less (2-6% approx. as against 20-50% in coal). Thus, the use of biomass in power generation will lead to substantial decrease in the amount of suspended particulate matters in the atmosphere.
- Energy content in biomass is more than those of E and F grade coals (mostly exploited coals in Indian power plants).
- Reactivity of biomass towards oxygen and carbon dioxide is much higher than that of coal. This permits the operation of boiler at lower temperatures resulting in greater saving of energy.
- Power generation on decentralized basis will reduce the transmission losses.
- Feasibility of installation of biomass gasifiers in any location or village.
- Easy availability of technology and backup systems.
- Support for the domestic and industrial waste management projects.

- Despite the above advantages, the rate of spread of biomass-based power generation systems is low due to a number of policy and financial barriers.
- Exploitation of biomass in power generation will lead to better utilization of barren lands of India (67 million hectares approx.).
- In planning the electricity generation from biomass on decentralized basis, the following points should be taken into account:
    - Kind, quality, quantity, feasibility of transportation and storage, sustainability and cost of biomass to be used.
    - Level of customer demand.
    - Method and cost of biomass drying.
    - Method of electricity generation and its economic viability.
    - Costs and qualities of locally available fossil fuels.

1.10 AIMS AND OBJECTIVES OF THE PRESENT PROJECT WORK

Following are the aims and objectives of the present investigation:

1. Selection of non-woody biomass species and estimation of their yield by field trial.
2. Determination of proximate analysis (% moisture, % volatile matter, % ash and % fixed carbon contents) of their different components, such as wood, leaf and nascent branch.
3. Mixed these biomass components separately with coal sample in different-different ratio.
4. Characterization of these biomass components for their energy values (calorific values).
5. Characterization of coal mixed biomass components for their energy values (calorific values).
6. Determination of ash fusion temperatures (IDT, ST, HT and FT) of ashes obtained from these biomass species and coal-biomass mixed sample.
7. Estimation of power generation potentials of these biomass species for a small thermal power plant on decentralized basis.
8. Comparative study of coal and mixed coal-biomass in different ratio of 95:05, 90:10, 85:15 and 80:20 with respect to selected biomass species.

CHAPTER-2

LITERATURE REVIEW

India’s energy challenges are multi–pronged (*Ravindranath et al, 2009*). They are manifested through growing demand for modern energy carriers, a fossil fuel dominated energy system facing a severe resource crunch, the need for creating access to quality energy for the large section of deprived population, vulnerable energy security, local and global pollution regimes and the need for sustaining economic development. Renewable energy is considered as one of the most promising alternatives. Recognizing this potential, India has been implementing one of the largest renewable energy programmes in the world. Among the renewable energy technologies, bioenergy has a large diverse portfolio including efficient biomass stoves, biogas, biomass combustion and gasification and process heat and liquid fuels. India has also formulated and implemented a number of innovative policies and programmes to promote bioenergy technologies. However, according to some preliminary studies, the success rate is marginal compared to the potential available. This limited success is a clear indicator of the need for a serious reassessment of the bioenergy programme. Further, a realization of the need for adopting a sustainable energy path to address the above challenges will be the guiding force in this reassessment. In this paper an attempt is made to consider the potential of bioenergy to meet the rural energy needs: (1) biomass combustion and gasification for electricity; (2) biomethanation for cooking energy (gas) and electricity; and (3) efficient wood-burning devices for cooking. The paper focuses on analysing the effectiveness of bioenergy in creating this rural energy access and its sustainability in the long run through assessing: the demand for bioenergy and potential that could be created; technologies, status of commercialization and technology transfer and dissemination in India; economic and environmental performance and impacts; bioenergy policies, regulatory measures and barrier analysis. The whole assessment aims at presenting bioenergy as an integral part of a sustainable energy strategy for India. The results show that bioenergy technology (BET) alternatives compare favourably with the conventional ones. The cost comparisons show that the unit costs of BET alternatives are in the range of 15–187% of the conventional alternatives. The climate change benefits in terms of carbon emission reductions are to the tune of 110 T C per year provided the available potential of BETs are utilized.

A majority of the Indian population does not have access to convenient energy services (LPG, electricity) (*Pillai et al, 2009*). Though India has made significant progress in renewable energy, the share of modern renewables in the energy mix is marginal. This paper reviews the status and potential of different renewables (except biomass) in India. The trends in the growth of renewables in India and establishes diffusion model as a basis for setting targets. The diffusion model is fitted tot the past trends for wind, small hydro and solar water heating and is used to establish future targets. The economic viability and greenhouse gas (GHG) saving potential is estimated for each option. Several renewables have high growth rates, for example wind, Photovoltaic (PV) module manufacture and solar water heaters. New technologies like Tidal, OTEC, Solar thermal power plants and geothermal power plants are at the demonstration stage and future dissemination will depend on the experience of these projects.

Bio-energy technologies (BETs) are presented as potential carbon abatement opportunities substituting fossil fuel or traditional (less efficient) biomass energy systems (*Ravindranath et al, 2006*). Cost of energy (produced or saved) of BETs is compared with fossil fuel and traditional biomass energy systems to estimate the incremental cost (IC). The IC of carbon abatement for each of the selected BETs (in $\$kWh^{-1}$ or $\$GJ^{-1}$) is estimated using the carbon emission ($tCkWh^{-1}$ or $tC\ GJ^{-1}$) reduction obtained by substituting fossil fuel and traditional biomass alternatives. The abatement costs are estimated and compared for ten combinations of BETs (with seven technology alternatives) substituting conventional technologies. The analysis indicates that out of the ten project cases six have negative ICs in the range of 37 to 688 $\$\ tC^{-1}$ and four have positive ICs in the range of 52–162 $\$\ tC^{-1}$ mitigation. The negative ICs indicate that the suggested alternatives are cheaper than the original technologies. Thus, results indicate that the chosen BETs are cost-effective mitigation opportunities and are currently aggressive candidates under Clean Development Mechanism.

In view of high energy potentials in non-woody biomass species and an increasing interest in their utilization for power generation (*Kumar and Patel, 2008*), an attempt has been made in this study to assess the proximate analysis and energy content of different components of *Ocimum canum* and *Tridax procumbens* biomass species (both non-woody) and their impact on power generation and land requirement for energy plantations. The net energy content in *Ocimum canum* was found to be slightly higher than that in *Tridax* *procumbens*. In spite of having higher ash contents, the barks from both the plant species exhibited higher calorific values. The results have shown that approximately 650 and 1,270 hectares of land are required to generate 20,000 kWh/day electricity from *Ocimum canum* and *Tridax procumbens* biomass species. Coal samples, obtained from six different local mines, were also examined for their qualities and the results were compared with those of studied biomass materials. This comparison reveals much higher power output with negligible emission of suspended particulate matters (SPM) from biomass materials.

The recent statements of both the European Union and the US Presidency pushed in the direction of using renewable forms of energy (*Angelis-Dimakis et al, 2010*), in order to act against climate changes induced by the growing concentration of carbon dioxide in the atmosphere. In this paper, a survey regarding methods and tools presently available to determine potential and exploitable energy in the most important renewable sectors (i.e., solar, wind, wave, biomass and geothermal energy) is presented. Moreover, challenges for each renewable resource are highlighted as well as the available tools that can help in evaluating the use of a mix of different sources.

Renewable energy sources and technologies have potential to provide solutions to the long-standing energy problems being faced by the developing countries (*Kumar et al, 2010*). The renewable energy sources like wind energy, solar energy, geothermal energy, ocean energy, biomass energy and fuel cell technology can be used to overcome energy shortage in India. To meet the energy requirement for such a fast growing economy, India will require an assured supply of 3–4 times more energy than the total energy consumed today. The renewable energy is one of the options to meet this requirement. Today, renewable account for about 33% of India's primary energy consumptions.

India is increasingly adopting responsible renewable energy techniques and taking positive steps towards carbon emissions, cleaning the air and ensuring a more sustainable future. In India, from the last two and half decades there has been a vigorous pursuit of activities relating to research, development, demonstration, production and application of a variety of renewable energy technologies for use in different sectors. In this paper, efforts have been made to summarize the availability, current status, major achievements and future potentials of renewable energy options in India. This paper also assesses specific policy interventions for overcoming the barriers and enhancing deployment of renewables for the future.

The heating value is one of the most important properties of biomass fuels for design calculations or numerical simulations of thermal conversion systems for biomass (*Sheng et al, 2005*). There are a number of formulae proposed in the literature to estimate the higher heating value (HHV) of biomass fuels from the basic analysis data, i.e. proximate, ultimate and chemical analysis composition. In the present paper, these correlations were evaluated statistically based on a larger database of biomass samples collected from the open literature. It was found that the correlations based on ultimate analysis are the most accurate. The correlations based on the proximate data have low accuracy because the proximate analysis provides only an empirical composition of the biomass. The correlations based on the bio-chemical composition are not reliable because of the variation of the components properties. The low accuracy of previous correlations is mainly due to the limitation of samples used for deriving them. To achieve a higher accuracy, new correlations were proposed to estimate the HHV from the proximate and ultimate analyses based on the current database. The new correlation between the HHV and dry ash content of biomass (in weight present, wt. %) (i.e. HHV (MJ/kg) = 19.914–0.2324 Ash) could be conveniently used to estimate the HHV from proximate analysis. The new formula, based on the composition of main elements (in wt. %) C, H and O (i.e. HHV (MJ/Kg) = -1:3675 + 0:3137C + 0:7009H + 0:0318O*), is the most accurate one, with more than 90% predictions in the range of ±5% error.

The key technical issues in woody biomass pre-treatment (*Zhu and Pan, 2010*): barriers to efficient cellulose saccharification, pre-treatment energy consumption, in particular energy consumed for wood-size reduction and criteria to evaluate the performance of a pre-treatment. A post-chemical pre-treatment size-reduction approach is proposed to significantly reduce mechanical energy consumption. Because the ultimate goal of biofuel production is net energy output, a concept of pre-treatment energy efficiency (kg/MJ) based on the total sugar recovery (kg/kg wood) divided by the energy consumption in pre-treatment (MJ/kg wood) is defined. It is then used to evaluate the performances of three of the most promising pre-treatment technologies: steam explosion, organosolv and sulphite pre-treatment to overcome lignocelluloses recalcitrance (SPORL) for softwood pre-treatment. The present study found that SPORL is the most efficient process and produced highest sugar yield. Other important issues, such as the effects of lignin on substrate saccharification and the effects of pre-treatment on high-value lignin utilization in woody biomass pre-treatment, are also discussed.

In India, fuel wood, crop residues and animal manure are the dominant biomass fuels (*Ravindranath et al, 2005*), which are mostly used in the rural areas, at very low efficiencies. Industrial and municipal (urban) residues such as wastewater, municipal solid wastes (MSW) and crop residues such as rice husk and bagasse can also be used for energy generation. In this paper, the potential of energy from crop residues, animal manure, MSW, industrial wastewater and biomass fuels that can be conserved for other applications through efficiency improvement is discussed. The total potential of energy from these sources in 1997 is estimated to be equivalent to 5.14 EJ, which amounts to a little more than a-third of the total fossil fuel use in India. The energy potential in 2010 is estimated to be about 8.26 EJ.

The potential for the use of renewable sources of energy in China and India and their cost effectiveness in air pollution abatement in Asia is studied (*Boudri et al, 2002*) This is done through an integrated assessment of the costs and the environmental impacts of several types of renewables, in comparison with fossil fuels. Results for different scenarios for fuel use in China and India for the period 1990–2020 are presented. The acidification model RAINS-ASIA is used to analyse environmental impacts (exceedance of critical loads for acidification) and to perform an optimization analysis, aiming at minimizing abatement costs. The costs of sulphur dioxide (SO_2) emission-control through the switch to renewable energy sources are analysed and compared with the costs of controlling the emissions from fossil fuels (e.g. through flue gas desulfurization). For the environmental targets analysed in this study an increased use of renewable energy could cut SO_2 emission control costs in China by 17–35% and in India by more than two thirds.

Postulates that Thailand has a high potential to utilize renewable energy for electricity generation especially from agricultural waste (*Santisirisomboon et al, 2000*); however, at present only a small fraction of biomass is used for energy purposes. This study aims to estimate the potential of biomass power generation and its impact on power generation expansion planning as well as mitigating carbon dioxide emission from the power sector. The harvest area and crop yield per area are taken into consideration to estimate the future biomass availability. The supplies of biomass are then applied as a constraint in the least cost electricity generation expansion-planning model. The cost of CO emissions is also added to the fuel costs as carbon taxation to make biomass power generation competitive to fossil fuels and then the optimum value of CO charge is found out. In addition, levels of CO limitation from power generation are also introduced to mitigate CO emissions.

Renewable energy is basic to reduce poverty and to allow sustainable development (*Goldemberg and Teixeira, 2004*). However, the concept of renewable energy must be carefully established, particularly in the case of biomass. This paper analyses the sustainability of biomass, comparing the so-called ‘‘traditional’’ and ‘‘modern’’ biomass and discusses the need for statistical information, which will allow the elaboration of scenarios relevant to renewable energy targets in the world.

Biomass-based energy devices developed in recent times (*Mukunda et al, 1994*). The need for this renewable energy for use in developing countries is first highlighted. Classification of biomass in terms of woody and powdery (pulverized) follows, along with comparison of its energetics with fossil fuels. The technologies involved, namely gasifier-combustor, gasifier-engine-alternator combinations, for generation of heat and electricity, are discussed for both woody biomass and powdery biomass in some detail. The importance of biomass to obtain high-grade heat through the use of pulverized biomass in cyclone combustors is emphasized. The techno economics is discussed to indicate the viability of these devices in the current world situation. The application packages where the devices will fit in and the circumstances favourable for their seeding are brought out. It is inferred that the important limitation for the use of biomass-based technologies stems from the lack of recognition of their true potential.

Calorific values of forest waste originating from forestry works such as woodland cleaning, reforestation and, all other silviculture tasks, were measured by static bomb calorimetry (*Regueira et al, 2001*). These waste materials, heretofore considered as useless refuse, are beginning to be used as alternative fuels in wide social sectors all over the world. Two of the main forest species, eucalyptus and pine existing in Galicia are included in this study. Some other parameters such as elementary chemical composition and heavy metal contents, moisture, density and ash percentage after combustion in the bomb, were also determined. The experimental results, with calorific values exceeding 20 000 kJ /kg make it advisable to use these materials as alternative fuel.

Proposed a method to evaluate and exploit the energetic resources contained in different forest formations (*Regueira et al, 2004*). This method is based on the use of a combustion bomb calorimeter to determine the calorific values of the different samples studied. These results were complemented with chemical analysis of the samples and with environmental and geomorphological studies of the zones, samples were taken.

Predicted ash fusion temperatures by using the chemical composition of the ash has previously been conducted only with linear correlations (*Ozbayoglu and Ozbayoglu, 2005*). In this study, a new technique is presented for predicting the fusibility temperatures of ash. Non-linear correlations are developed by using the chemical composition of ash (eight oxides) and coal parameters (ash content, specific gravity, Hardgrove index and mineral matter content). Regression analyses are conducted using information for Turkish lignites. Regression coefficients and variances of nonlinear and linear correlations are compared. The results show that the non-linear correlations are superior to linear correlations for estimating ash fusion temperatures.

Potential applications of renewable energy sources to replace fossil fuel combustion as the prime energy sources in various countries and discusses problems associated with biomass combustion in boiler power systems (*Demirbas*, *2005*). Here, the term biomass includes organic matter produced as a result of photosynthesis as well as municipal, industrial and animal waste material. Biomass is an attractive renewable fuel in utility boilers. The compositions of biomass among fuel types are variable. Ash composition for the biomass is fundamentally different from ash composition for the coal. Especially inorganic constituents cause to critical problems of toxic emissions, fouling and slagging. Metals in ash, in combination with other fuel elements such as silica and sulphur and facilitated by the presence of chlorine, are responsible for many undesirable reactions in combustion furnaces and power boilers. Elements including K, Na, S, Cl, P, Ca, Mg, Fe and Si are involved in reactions leading to ash fouling and slagging in biomass combustors. Chlorine in the biomass may affect operation by corrosion. Ash deposits reduce heat transfer and may also result in severe corrosion at high temperatures. Other influences of biomass composition are observed for the rates of combustion and pollutant emissions. Biomass combustion systems are non-polluting and offer significant protection of the environment. The reduction of greenhouse gases pollution is the main advantage of utilizing biomass energy.

CHAPTER-3

EXPERIMENTAL WORK

3.1 SELECTION OF MATERIALS

In the present project work, two different types of non-woody biomass species Cassia Tora (Local Name: Chakunda) and gulmohar (Local name: Krishnachura) where procured from the local area. These biomass species were cut into different pieces and there different component like leaf, nascent branch and main branch were separation from each other. These biomass materials were air-dried in cross ventilator room for around 20 days. When the moisture contains of these air-dried biomass sample came in equilibrium with that of the air, they were crushed in mortar and pestle into powder of -72 mess size.

Coal sample for making the blend was collected from Lingaraj mines of Orissa. These materials were than processed for the determination their proximate analysis and Energy values.

Fig. 3.1: Sample of biomass component, component powder and coal powder

3.2 PROXIMATE ANALYSIS

Proximate Analysis consist of moisture, ash, volatile matter, and fixed carbon contents determination were carried out on samples ground to -72 mess size by standard method. The details of these analysis are as follows;

3.2.1 Determination of Moisture

One gm. (1 gm.) of air dried -72 mess size powder of the above said materials was taken in borosil glass disc and heated at a temperature of $105^0C \pm 5^0C$ for one hour in air oven. The discs were then taken out the oven and the materials were weight. The percentage loss in weight was calculated which gives the percentage (%) moisture contains in the sample.

3.2.2 Determination of Ash Content

One gm. (1 gm.) of -72 mess size (air dried) was taken in a shallow silica disc and kept in a muffle furnace maintained at the temperature of 775^0C ± 5^0 C. The materials were heated at this temperature for one hour or till complete burning. The weight of the residue was taken in an electronic balance. The percentage weight of residue. Weight of obtained gives the ash contained in the sample.

% Ash = Wt. of residue obtained × 100 / Initial wt. of simple.

3.2.3 Determination of Volatile Matter

One gm. (1 gm.) of -72 mess size (air dried) powder of the above said materials was taken in a volatile matter crucible (cylindrical in shape and made of silica). The crucible is covered from top with the help of silica lid. The crucible were placed in a muffle furnace, maintained at the temperature of 925^0 C ± 5^0 C and kept there for 7 minute. The volatile matter crucibles were then taken out from the furnace and cooled in air. The devolatized samples were weighted in an electronics balance and the percentage loss in weight in each of the sample was calculated. The percentage volatile matter in the sample was determined by using the following formula

% volatile matter (VM) = % lass in weight - % moisture

3.2.4 Determination of Fixed Carbon

The fixed carbons in the simple were determined by using the following formula.

% FC = 100 ─ (% M + % VM + % Ash)

Where, FC: Fixed carbon, M: Moisture, VM: Volatile Matter

3.3 CALORIFIC VALUE DETERMINATION

The calorific values of these species (-72 mesh size) were measured by using an Oxygen bomb calorimeter (BIS, 1970, shown in Fig.3.3); 1 gm. of briquetted sample was taken in a nicron crucible. A 15 cm long cotton thread was placed over the sample in the crucible to facilitate in the ignition. Both the electrodes of the calorimeter were connected by a nicrom fuse wire. Oxygen gas was filled in the bomb at a pressure of around 25 to 30 atm. The water (2 lit.) taken in the bucket was continually starred to homogeneous the temperature. The sample was ignited by switching on the current through the fussed wire and the rise in temperature of water was automatically recorded. The following formula was used to determine the energy value of the sample.

Gross calorific value (GCV) = {(2500 × ΔT) / (Initial wt. of simple) — (heat released by cotton thread + Heat released by fused wire)}

Where, 2500 is the water equivalent water apparatus and DT in the max^{im} rising temperature.

Fig. 3.2: Briquetted sample

Fig. 3.3: Oxygen Bomb Calorimeter (BIS, 1970)

3.4 ASH FUSION TEMPERATURE DETERMINATION

The ash fusion Temperature, softening Temperature, Hemispherical temperature and Flow temperature) of all the ash samples,obtained from the presently selected non-woody biomass species and coal-biomass (in ratio) mixed sample were determined by using Leitz Heating Microscope (LEICA shown in Fig.3.4) in Material Science Centre of the Institute. The appearance of ash samples at IDT, ST, HT and FT are shown in Fig. 3.5.

Fig. 3.4: Leitz Heating Microscope

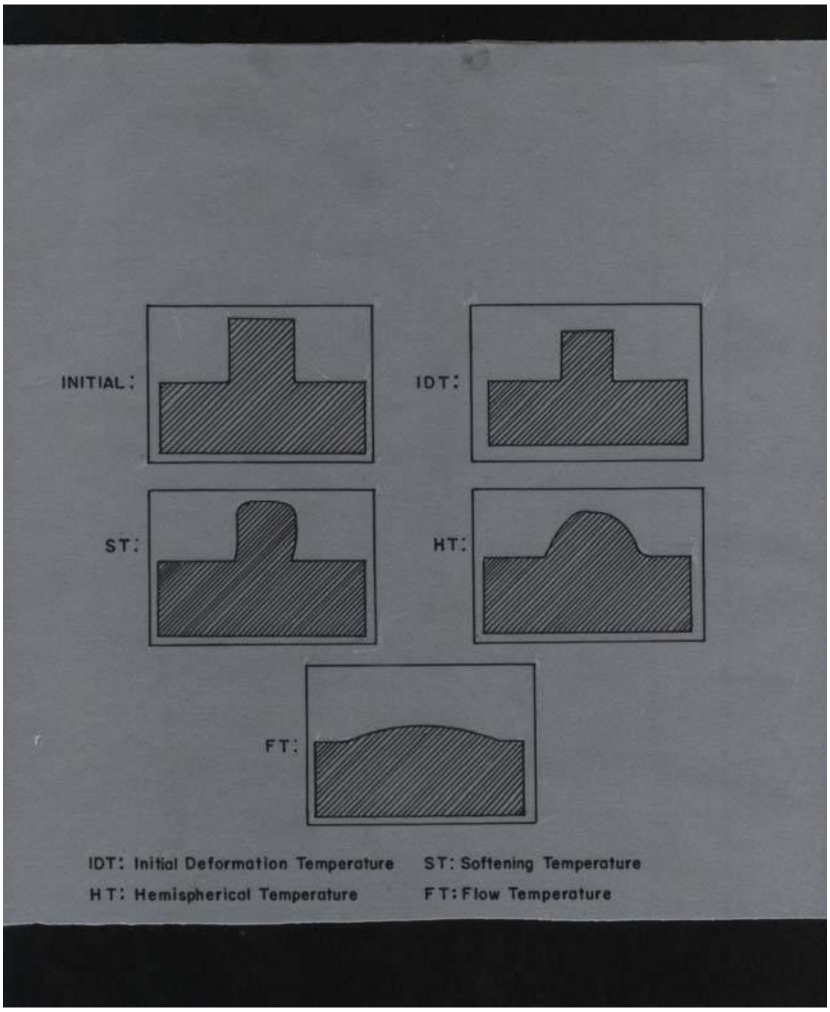


Fig. 3.5: Shapes of Ash Samples at Four Different Characteristics of Ash Fusion Temperature

CHAPTER-4

RESULTS AND DISCUSSION

4.1 PROXIMATE ANALYSIS OF PRESENTLY SELECTED NON-WOODY BIOMASS PLANT COMPONENTS AND COAL BIOMASS MIXED BRIQUETTES

Freshly chopped non-woody biomass components have a large amount of free moisture, which must be removed to decrease the transportation cost and increase the calorific value. In the plant species selected for the present study, the time required to bring their moisture contents into equilibrium with that of atmosphere was found to be in the range of 15 to 20 days during the summer season (temperature :35-45°C and moisture: 6-14%).

The studies of the proximate analysis of fuels /energy sources are important because they give an approximate idea about the energy values and extent of pollutants emissions during combustion. The proximate analysis of different components of Gulmohar and Cassia Tora plant and these biomass species component briquettes with coal are presented in Tables 4.1 – 4.5. The data for proximate analysis of the components of these species are very close to each other and hence it is very difficult to draw a concrete conclusion. However, it appears from these tables that Cassia Tora biomass species has somewhat higher ash and lower fixed carbon contents than these of Gulmohar biomass species and the ash contents being more and volatile matter is less when 95% coal mixing with 5% biomass and 90% coal mixing with 10% biomass but when 85% coal mixing with 15% biomass and 80% coal mixing with 20% biomass then ash content is being less and volatile matter is more.

4.2 CALORIFIC VALUES OF PRESENTLY SELECTED NON-WOODY BIOMASS PLANT COMPONENTS

The calorific values of the fuels/energy source are important norms for judging its quality to be used in electricity generation in power plants. It provides an idea about the energy value of the fuel and the amount of electricity generation.

Calorific values data listed in Table 4.1 & 4.2 indicate that among all the studied biomass species, calorific values of wood component of both biomasses have higher in comparison to leaf and nascent branch. Gulmohar biomass species were found to be little bit higher than that of Cassia Tora biomass. Table 4.4 & 4.5 are shows that calorific value of coal mixed Gulmohar biomass (different component in different ratio) were found to be higher than that of coal mixed cassia tora biomass (different component in different ratio).

Amongst the four different ratios, ratio 80:20 gives the highest energy value in all mixed component and 85:15 also gives higher energy value except leaf component of both biomass in respect to other two ratios (95:05 and 90:10).

Comparison of data listed in Table 4.1-4.3 shows that in difference to coals included in the present study, both non-woody biomass materials have considerably higher calorific values and very lower ash contents. Table 4.4 & 4.5 indicates that calorific values of biomass species are something lower but ash content are also lower in compare to coal. This is definitely an benefit over fossil fuels. It is thus clear that these non-woody biomass resources will result in higher power production in the plant with slight emission of suspended particulate matters (SPM).

4.3 ASH FUSION TEMPERATURE OF PRESENTLY STUDIED NON-WOODY BIOMASS SPECIES

It also experimentally finds out the ash fusion temperatures to confirm its safe operation in the boiler. Ash fusion temperature of solid fuel is an important parameter affecting the operating temperature of boilers. Clinker creation in the boiler usually occurs due to low ash fusion temperature and this hampers the operation of the boiler. Hence the study of the ash fusion temperature of solid fuel is essential before its operation in the boiler. The four characteristic ash fusion temperatures were identified as: (i) initial deformation temperature (IDT) – first sign of change in shape; (ii) softening temperature (ST) – rounding of the corners of the cube and shrinkage; (iii) hemispherical temperature (HT) – deformation of cube to a hemispherical shape; and (iv) fluid temperature (FT) – flow of the fused mass in a nearly flat layer. The shapes of the initially taken cubic ash samples at IDT, ST, HT and FT are shown in Fig. 3.3. Identical shapes at these temperatures were obtained for all the studied non-woody biomass species like Gulmohar, cassia tora and coal mixed these biomass. Data for the ash fusion temperatures (IDT, ST, HT and FT) for have been listed in Table 4.6.

4.4 ELECTRICITY GENERATION SYSTEM

The biomass based electricity generation method is outlined in Figure 1.6 freshly cut wood holds a large amount of moisture, which must be removed to decrease the transportation cost and to increase the energy density (i.e. calorific value). The carbonization of biomass yields charcoal as main product and generates a large amount (approximately 65-75 % of the weight of biomass) of volatile matter (pyrolytic gas). For the biomass energy system to be competitive and to increase energy conversion efficiency, technologies available for promoting power generation from biomass are gasification, combustion, co-combustion and bio-methanation. The pyrolytic gas should also be combusted to generate electricity. The ash obtained would be transported back to the plantation centre and used as a fertilizer, or it could be utilized as building material.

4.5 PROXIMATE ANALYSIS AND CALORIFIC VALUE OF DIFFERENT COMPONENTS OF NON-WOODY BIOMASS SPECIES AND COAL

The results obtained from proximate analysis and calorific value of non-woody biomass species, coal, coal-biomass mixed briquettes and Ash fusion temperatures of selected biomass species and coal- biomass mixed (in ratio) during the course of this project work have been summarized in Tables 4.1– 4.6 and presented graphically in Figs. 4.1-4.9.

Table 4.1: Proximate Analysis of Gulmohar (Local name: Krishnachura)

Component	Proximate Analysis (Wt. %, air-dried basis)				Gross Calorific Value (Kcal/ kg, Dried Basis)
	Moisture	Ash	Volatile Matter	Fixed Carbon	
Wood	9.00	3.00	72.68	15.00	4549
Leaf	8.90	7.20	70.11	15.00	3947
Nascent branch	9.80	4.20	70.05	14.22	4061

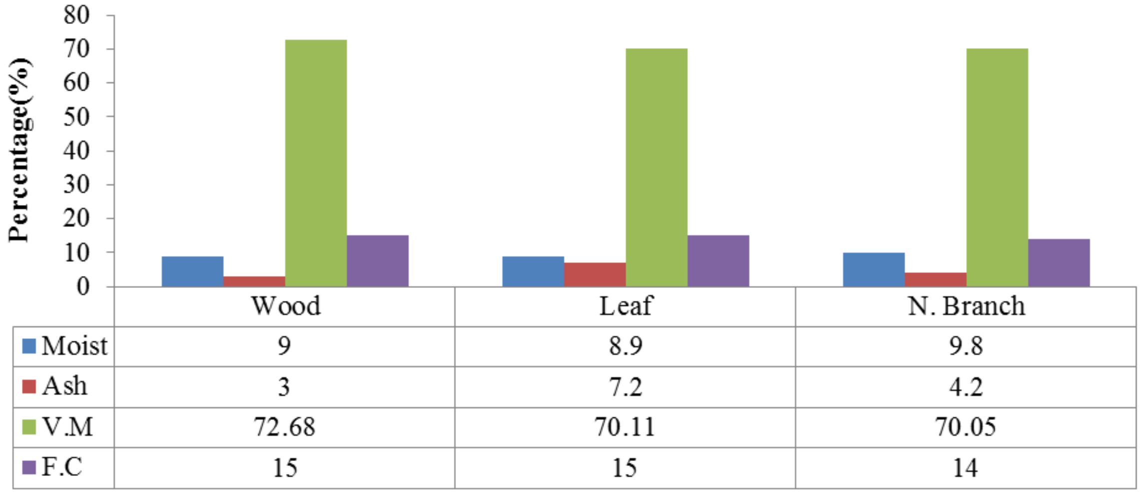


Fig. 4.1: Variation of Proximate Analysis of Gulmohar Biomass

Table 4.2: Proximate Analysis of Cassia Tora (local name: Chakunda)

Component	Proximate Analysis (Wt. %, air-dried basis)				Calorific Value (Kcal/ kg, Dried Basis)
	Moisture	Ash	Volatile Matter	Fixed Carbon	
Wood	11.00	7.80	68.50	12.00	4344
Leaf	11.50	7.40	69.00	14.00	4113
Nascent branch	10.00	5.20	70.00	14.00	3697

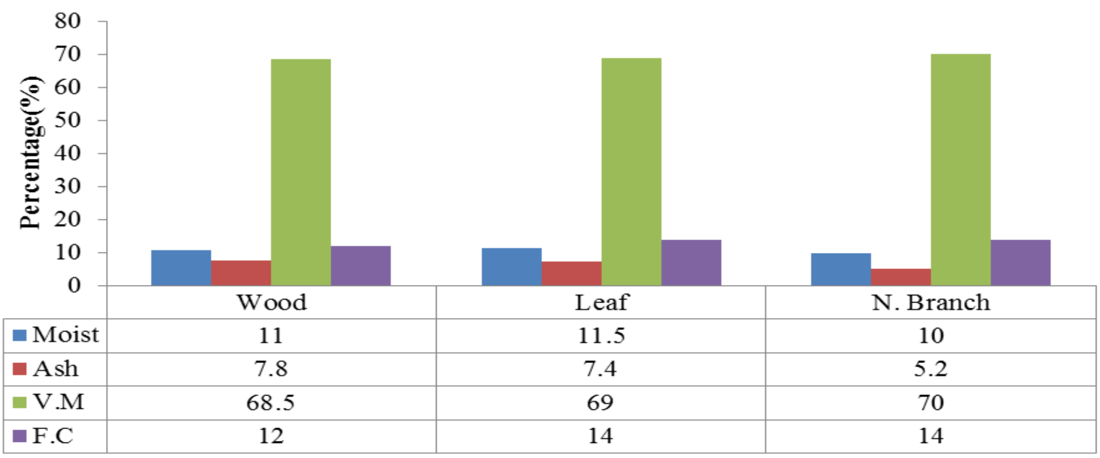


Fig.4.2: Variation of Proximate Analysis of Cassia Tora Biomass

Table 4.3: Proximate Analysis of Non-coking coal

Component	**Proximate Analysis (Wt. %, air-dried basis)**				**Calorific Value (Kcal/ kg, Dried Basis)**
	Moisture	**Ash**	**Volatile Matter**	**Fixed Carbon**	
Lingaraj Mines	8.90	41.20	21.70	29	4237

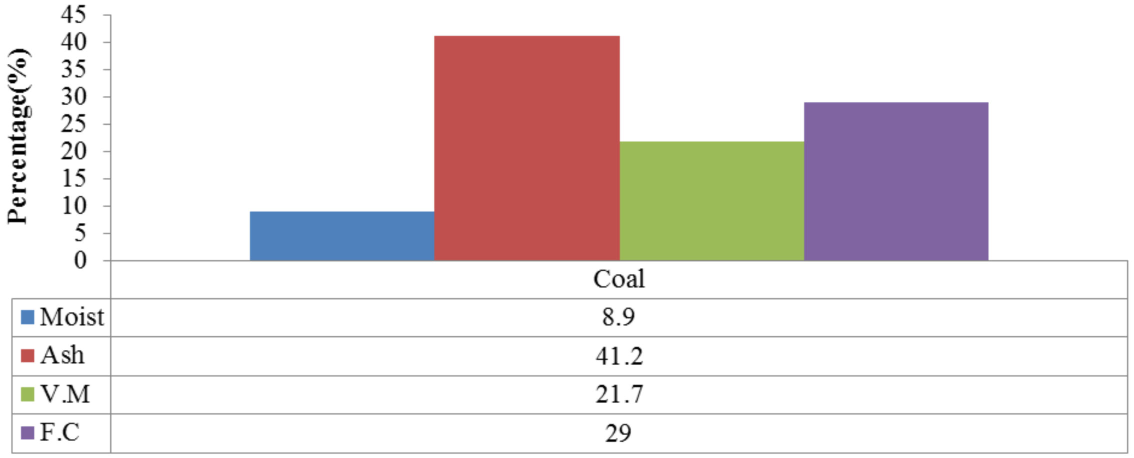
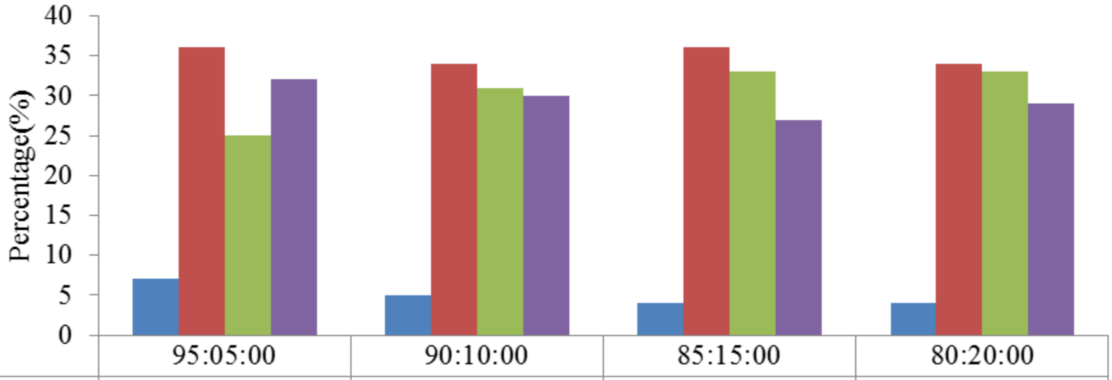


Fig. 4.3: Variation of Proximate Analysis of Non-coking Coal

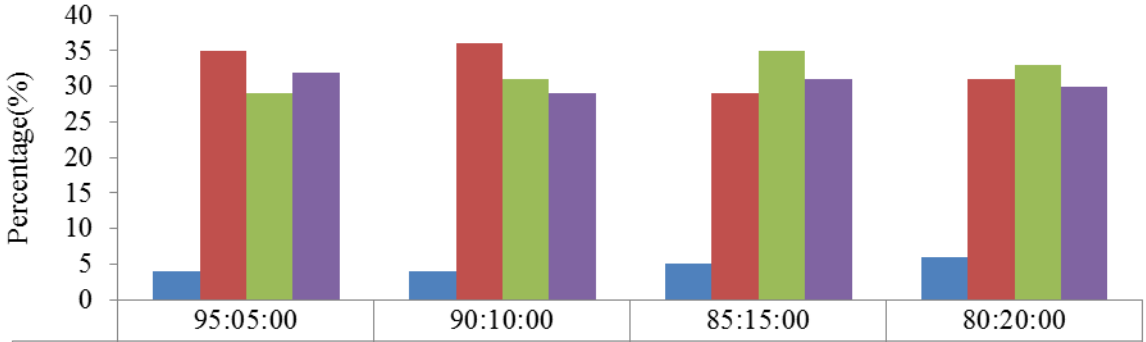
Table 4.4: Coal: Gulmohar Biomass Different Component

Ratio (Coal: Biomass)	Proximate Analysis (Wt. %, Air Dried Basis)				Calorific value (Kcal/ kg, Dried Basis)
	Moisture	Ash	Volatile Matter	Fixed Carbon	
Main wood					
95:05	7	36	25	32	3214
90:10	5	34	31	30	3497
85:15	4	36	33	27	3748
80:20	4	34	33	29	4087
Leaf					
95:05	4	35	29	32	3422
90:10	4	36	31	29	3483
85:15	5	29	35	31	3077
80:20	6	31	33	30	3830
Nascent Branch					
95:05	4	37	32	27	3584
90:10	3	33	35	29	3551
85:15	6	29	39	26	3557
80:20	7	30	42	21	3801



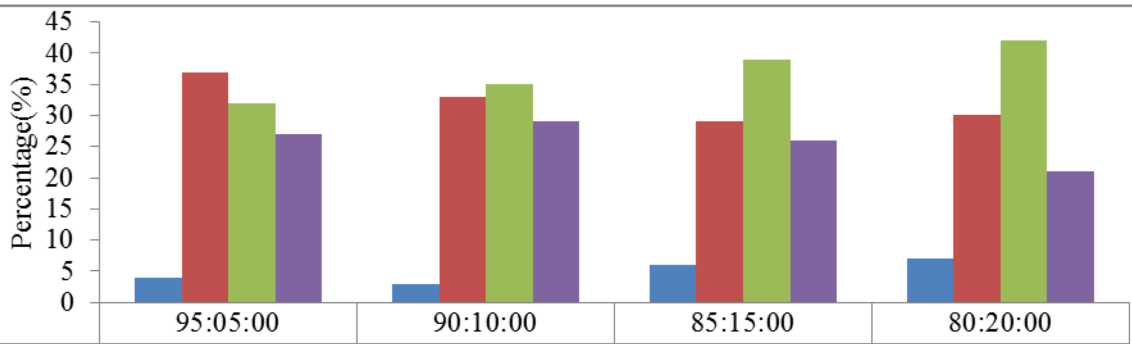
	95:05:00	90:10:00	85:15:00	80:20:00
Moist	7	5	4	4
Ash	36	34	36	34
V.M	25	31	33	33
F.C	32	30	27	29

Fig4.4: Variation of Mixture of Coal and Gulmohar Biomass(Wood)



	95:05:00	90:10:00	85:15:00	80:20:00
Moist	4	4	5	6
Ash	35	36	29	31
V.M	29	31	35	33
F.C	32	29	31	30

Fig.4.5: Variation of Mixture of Coal and Gulmohar Biomass(Leaf)

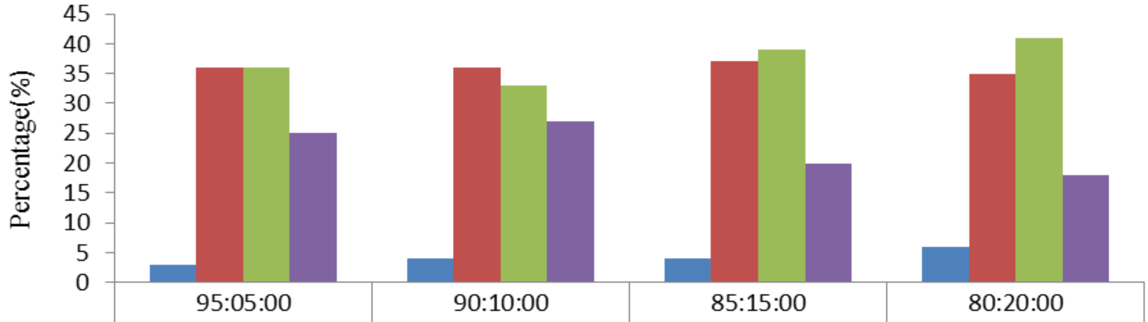


	95:05:00	90:10:00	85:15:00	80:20:00
Moist	4	3	6	7
Ash	37	33	29	30
V.M	32	35	39	42
F.C	27	29	26	21

Fig. 4.6: Variation of Mixture of Coal and Gulmohar Biomass(Nacent Branch)

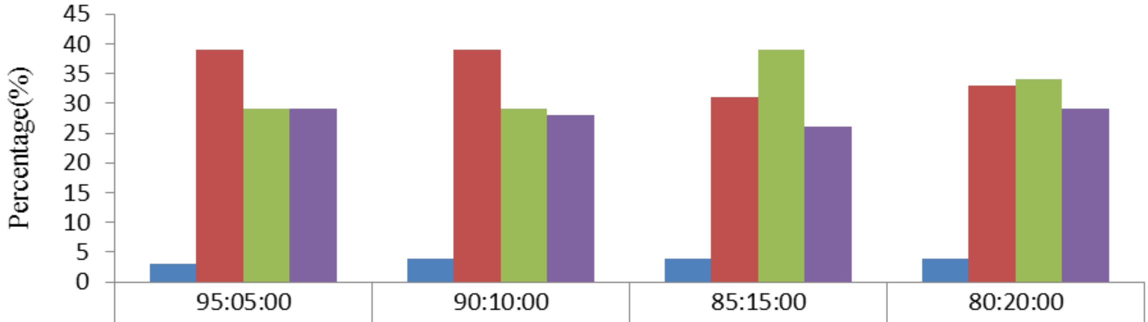
Table 4.5: Coal: Cassia Tora Biomass Different Component

Ratio (Coal: Biomass)	Proximate Analysis (Wt. %, Air Dried Basis)				Calorific value (Kcal/ kg, Dried Basis)
	Moisture	Ash	Volatile Matter	Fixed Carbon	
Main wood					
95:05	3	36	36	25	3146
90:10	4	36	33	27	2980
85:15	4	37	39	20	3482
80:20	6	35	41	18	3454
Leaf					
95:05	3	39	29	29	3275
90:10	4	39	29	28	3668
85:15	4	31	39	26	3051
80:20	4	33	34	29	4143
Nascent Branch					
95:05	4	39	32	25	3471
90:10	7	37	29	27	3211
85:15	3	31	39	27	3675
80:20	3	36	39	22	3672



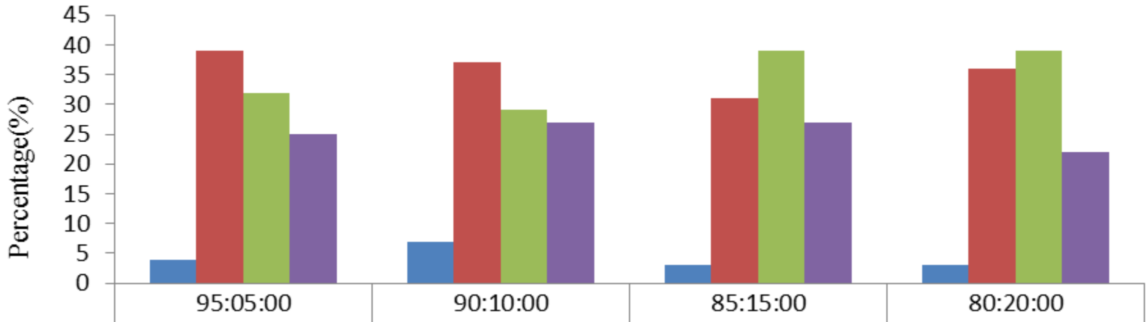
	95:05:00	90:10:00	85:15:00	80:20:00
Moist	3	4	4	6
Ash	36	36	37	35
V.M	36	33	39	41
F.C	25	27	20	18

Fig. 4.7: Variation of Mixture of Coal and Cassia Tora(Wood)



	95:05:00	90:10:00	85:15:00	80:20:00
Moist	3	4	4	4
Ash	39	39	31	33
V.M	29	29	39	34
F.C	29	28	26	29

Fig.4.8: Variation of Mixture of Coal and Cassia Tora(Leaf))



	95:05:00	90:10:00	85:15:00	80:20:00
Moist	4	7	3	3
Ash	39	37	31	36
V.M	32	29	39	39
F.C	25	27	27	22

Fig. 4.9: Variation of Mixture of Coal and Cassia Tora(Nacent Branch)

Table 4.6: Ash Fusion Temperatures of Selected Biomass Species and Coal- Biomass Mixed Sample

Biomass Species / Coal-Biomass Mixed Ratio	**Ash Fusion Temperatures(°C)**			
	IDT	**ST**	**HT**	**FT**
Cassia Tora	893	1245	>1400	>1400
Gulmohar	1058	1249	>1400	>1400
Coal : Biomass (90:10)	1160	1297	>1400	>1400
Coal : Biomass (80:20)	1188	1298	>1400	>1400

IDT: Initial Deformation Temperature

ST: Softening Temperature

HT: Hemispherical Temperature

FT: Flow Temperature

4.6 CALCULATIONS

Table 4.7: Total Energy Contents and Power Generation Structure from 8 Months old (approx.), Gulmohar Plants

Component	Calorific Value (kcal/t, dry basis)	Biomass Production (t/ha, dry basis)	Energy Value (kcal/ha)
Main wood	4532×10^3	21.00	95172×10^3
Leaf	3907×10^3	7.00	27349×10^3
Nascent branch	3997×10^3	9.50	37971.5×10^3

* Data from filed studies (biomass production)

Energy Calculation:

On even dried basis, total energy from one hectare of land

$= (95172+27349+37971.5) \times 10^3$

$= 160492.5 \times 10^3$ kcal

It is assumed that conversion efficiency of wood fuelled thermal generators = 26 % and mechanical efficiency of the power plant = 85 %.

Energy value of the total functional biomass obtained from one hectare of land at 26% conversion efficiency of thermal power plant $= 160492.5 \times 10^3 \times 0.26$

$= 41728.05\times 10^3$

$= 41728.05\times 10^3 \times 4.186 \div 3600$

$= 48520.45$ kWh

Power generation at 85 % mechanical efficiency

$= 48520.45 \times 0.85$

$= 41242.38$ kWh/ha

Land required to supply electricity for entire year

$=73\times 10^5 / 41242.38$

= 177 hectares

Table 4.8: Total Energy Contents and Power Generation Structure from 4 Months old (approx.), Cassia Tora Plants

Component	**Calorific Value (kcal/t, dry basis)**	**Biomass Production (t/ha, dry basis)**	**Energy Value (kcal/ha)**
Main wood	4344×10^3	4.00	17376×10^3
Leaf	4013×10^3	1.50	6019.5×10^3
Nascent branch	3672×10^3	2.50	9180×10^3

* Data from filed studies (biomass production)

Energy Calculation:

On even dried basis, total energy from one hectare of land

$= (17376+6019.5+9180) \times 10^3$

$= 32575 \times 10^3$ kcal

It is assumed that conversion efficiency of wood fuelled thermal generators = 26 % and mechanical efficiency of the power plant = 85 %.

Energy value of the total functional biomass obtained from one hectare of land at 26% conversion efficiency of thermal power plant $= 32575.5 \times 10^3 \times 0.26$

$= 8469.63\times 10^3$ kcal

$= 8467.29\times 10^3 \times 4.186 \div 3600$

$= 9848.30$ kWh

Power generation at 85 % mechanical efficiency

$= 9848.30\times 0.85$

$= 8371.05$ kWh/ha

Land required to supply electricity for entire year

$=73\times 10^5 / 8371.05$

$= 872.05$ hectares

CHAPTER-5

CONCLUSIONS

5.1 CONCLUSIONS

In the present work two non-woody biomass species Gulmohar and Cassia Tora were selected. Experiments to determine the proximate analysis, calorific values and ash fusion temperature was done on each of the components of the selected species such as main wood; leaf and nascent branch were performed. Estimation was done to analyse how much power can be generated in one hectare of land from each of these species. The following are the different conclusions drawn from the present work:

1. Both plant species (Gulmohar and Cassia tora) showed almost the similar proximate analysis results for their components, the ash contents being more in their leaves and volatile matter content less in Cassia tora wood and leaf.
2. Mixed ratio of Both biomass with coal(in four different ratio) also showed the same proximate analysis results, the ash contents being more when 95% coal mixing with 5% biomass and volatile matter is more when 80% coal mixing with 20% biomass.
3. The non-wood biomass species showed highest energy values for their branch, followed by wood, leaf and nascent branch.
4. Amongst the both biomass species Gulmohar has the highest energy value compared to Cassia tora.
5. Amongst the four different ratio, ratio 80:20 gives the highest energy value compared to 95:05, 90:10, 85:15.
6. Energy values of coal mixed Gulmohar biomass component were found to be little bit higher than that of coal mixed Cassia Tora biomass component.
7. Calculation results have established that nearly 177 and 872 hectares of land would be required for continuous generation of 41242.38 kWh per hectares from Gulmohar and 8371.05 kWh per hectares from Cassia tora biomass species.
8. The ash fusion temperature of all the species are coming above the range of boiler operation, this would avoid clinker formation in the boiler.
9. This study could be positive in the exploitation of non-woody biomass species for power generation.

5.2 SCOPE FOR FUTURE WORK

The present study was concentrated on two non-woody biomass species such as Gulmohar and Cassia Tora. The following works are suggested to be carried out in future.

- Similar type of study need to be extended for another non-woody biomass species available in the local area.
- The biomass species may be mixed with cow dunk, sewage wastes, etc. in different ratios and the electricity generated potentials of the mixtures may be determined.
- Pilot plant study on laboratory scale may be carried out to generate electricity from biomass species.
- The powdered samples of these biomass species may be mixed with cow dunk and the electricity generated potential of the resultant mixed briquettes may be studied.
- New techniques of electricity generation from biomass species may be developed

REFERENCES

1. Angelis-Dimakis A., Biberacher M. and Dominguez J., Methods and tools to evaluate the availability of renewable energy sources, Renewable and Sustainable Energy Reviews, 15 (2011): pp. 1182-1200
2. Boudri J.C., Hordijk L., Kroeze C. and Amann M., The potential contribution of renewable energy in air pollution abatement in China and India, Energy Policy, 30 (2002): pp. 409–424
3. Demirbas A., Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues, Progress in Energy and Combustion Science, 31 (2005): pp. 171–192
4. Goldemberg J. and Teixeira Coelho S., Renewable energy—traditional biomass vs. modern biomass, Energy Policy, 32 (2004): pp. 711–714
5. International Energy Agency (IEA): www.iea.org/Textbase/techno/essentials.htm
6. http://www.ireda.gov.in
7. Kumar M. and Patel S.K., Energy Values and Estimation of Power Generation Potentials of Some Non-woody Biomass Species, Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 30:8, (2008): pp. 765 – 773
8. Kumar A., Kumar K. and Kaushik N., Renewable energy in India: Current status and future potentials- Renewable and Sustainable Energy Reviews, 14 (2010): pp. 2434–2442
9. Ministry of New & Renewable Energy (MNRE): http://mnre.gov.in/prog-biomasspower.htm
10. Mukunda H.S., Dasappa S., Paul P. J., Rajan N.K.S. and Shrinivasa U., Gasifiers and combustors for biomass technology and field studies, Energy for Sustainable Development.1 (1994): pp. 27-38
11. Ozbayoglu G. and Ozbayoglu M.E., A new approach for the prediction of ash fusion temperatures: A case study using Turkish lignites, Fuel, 85 (2006): pp.545-552
12. Pillai I.R. and Banerjee R., Renewable energy in India: Status and potential, Energy, 34 (2009): pp. 970–980
13. Ravindranath N.H. and Balachandra P., Sustainable bioenergy for India: technical, economic and policy analysis, Energy, 34 (2009): pp. 1003–1013

14. Ravindranath N.H, Somashekar H.I., Nagaraja M.S., Sudh P. and Bhattacharya S.C., Assessment of sustainable non-plantation biomass resources potential for energy in India, Biomass and Bioenergy, 29 (2005): pp. 178–190
15. Ravindranath N.H., Balachandra P., Dasappa S. and Rao Usha K., Bioenergy technologies for carbon abatement, Biomass and Bioenergy, 30 (2006): pp. 826–837
16. Regueira L.N., Anon J. A. R., Castineiras J. P., Diz A. V. and Santovena N. M., Determination of calorific values of forest waste biomass by static bomb calorimetry, Thermochimica Acta, 371 (2001): pp. 23-31
17. Regueira L.N., Castineiras J. P. and Anon J. A., Design of an experimental procedure for energy evaluation from biomass, Thermochemica Acta, 420 (2004): pp. 29-31
18. Santisirisomboon J. and Limmeechokchai B., Impacts of biomass power generation and CO2 taxation on electricity generation expansion planning and environmental emissions, Fuel and Energy Abstracts, Energy Policy, 29 (2001): pp. 975-985
19. Sheng C. and Azevedo J.L.T., Estimating the higher heating value of biomass fuels from basic analysis data, Biomass and Bioenergy, 28 (2005): pp. 499–507
20. Zhu J.Y. and Pan X.J., Woody biomass pre-treatment for cellulosic ethanol production: Technology and energy consumption evaluation, Bio resource Technology, 101 (2010): pp. 4992–5002